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Effect of pruning intensity on soil moisture and water use efficiency in jujube (*Ziziphus jujube* Mill.) plantations in the hilly Loess Plateau Region, China

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Abstract: Jujube (*Ziziphus jujube* Mill.) is a traditional economic forest crop and is widely cultivated in hilly areas of the Loess Plateau, China. However, soil desiccation was discovered in jujube plantations. Pruning is recognized as a water-saving method that can reduces soil water consumption. In this study, we monitored the jujube plots with control (CK), light (C_1), medium (C_2) and high (C_3) pruning intensities during the jujube growing period of 2012–2015 to explore the effect of pruning intensity on soil moisture and water use efficiency (WUE) of jujube plantations in the hilly Loess Plateau Region. The results showed that pruning is an effective method for soil water conservation in jujube plantations. Soil moisture increased with increasing pruning intensity during the jujube growing period of 2012–2015. C_1, C_2 and C_3 pruning intensities increased soil water storage by 6.1–18.3, 14.4–40.0 and 24.3–63.3 mm, respectively, compared to CK pruning intensity. Pruning promoted soil moisture infiltration to deeper soil layer. Soil moisture infiltrated to soil depths of 240, 280 and >300 cm under C_3 pruning intensity, 220, 260 and 260 cm under C_2 pruning intensity, 200, 240 and 220 cm under C_1 pruning intensity, and 180, 200 and 160 cm under CK pruning intensity in 2013, 2014 and 2015, respectively. Soil water deficit was alleviated by higher pruning intensity. In 2013–2015, soil water change was positive under C_2 (6.4 mm) and C_3 (26.8 mm) pruning intensities but negative under C_1 (–20.5 mm) and CK (–40.6 mm) pruning intensities. Moreover, pruning significantly improved fresh fruit yield and WUE of jujube plants. Fresh fruit yields were highest under C_1 pruning intensity with the values of 6897.1–13,059.3 kg/hm^2, which were 2758.4–4712.8, 385.7–1432.1 and 802.8–2331.5 kg/hm^2 higher than those under CK, C_2, and C_3 pruning intensities during the jujube growing period of 2012–2015, respectively. However, C_3 pruning intensity had the highest WUE values of 2.92–3.13 kg/m^3, which were 1.6–2.0, 1.1–1.2 and 1.0–1.1 times greater than those under CK, C_1 and C_2 pruning intensities, respectively. Therefore, C_3 pruning intensity is recommended to jujube plantations for its economic and ecological benefits. These results provide an alternative strategy to mitigate soil desiccation in jujube plantations in the hilly Loess Plateau Region, which is critical for sustainable cultivation of economic forest trees in this region.

Keywords: pruning intensity; soil desiccation; yield; water use efficiency; *Ziziphus jujube* Mill.; Loess Plateau

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1 Introduction

The inappropriate selection of forest species and overemphasis on tree and shrub planting in vegetation construction and environmental restoration have caused soil desiccation and widespread dried soil layer in artificial forests and grasslands in the hilly Loess Plateau Region of China (Li, 1983; Shangguan, 2007; Chen et al., 2008; Fu et al., 2012; Jia et al., 2017; Gao et al., 2018). In arid and semi-arid areas, excessive depletion of deep soil moisture due to inappropriate vegetation types and long-term drought has made ecological restoration through land use change be difficult (Chen et al., 2008). Soil desiccation also occurs in many other areas of the world, such as Russia, eastern Amazonia and Brazil, where the amount of annual rainfall is lower than that of annual water use (Yang and Han, 1985; Jipp et al., 1998; Oliveira et al., 2005; Robinson et al., 2006).

Jujube (*Ziziphus jujube* Mill.) is an important traditional economic forest species in the hilly Loess Plateau Region, China. Its cultivated area exceeds 6.67×10^{4} hm^{2} as a major agroforestry industry in this region. However, dried soil layer is found in jujube plantations due to high planting intensity and extensive and low-level management model. The depth of dried soil layer in a twelve-year-old jujube plantation can reach up to 540 cm (Wang et al., 2015) and there almost has no available water in the 200–400 cm soil layer in a nine-year-old jujube plantation (Liu et al., 2014). This suggests that the degree of soil water deficit is worsened over time in jujube plantations (Xin et al., 2012). And if the current planting pattern continues, the hydrological and ecological environment will eventually be irreparably damaged.

Many studies have been conducted to determine the formation and characteristics of soil desiccation or dried soil layer in cultivated lands (Wang and Shao, 2004; Chen et al., 2005; Shao et al., 2016). Researchers have also proposed some measures, such as crop rotation, mulching and appropriate mixed tree/shrub planting, to alleviate soil water depletion especially in arid and semi-arid regions (Wang et al., 2008; Fang et al., 2010; Wang et al., 2012; Fan et al., 2014; Gao et al., 2018).

Pruning is a common agronomic method used to increase crop yield and fruit quality (Martin et al., 1980; Max et al., 2016), because it can change vegetation structure, improve light energy utilization (Yang et al., 1998; Forrester et al., 2012) and increase fruit setting rate and soluble sugar content (Pei et al., 2013). Recently, pruning is recognized as a water-saving method that can reduce soil water consumption (Shelden and Sinclair, 2000; López et al., 2008; Alcorn et al., 2013). Jackson et al. (2000) reported that tree pruning has been used as a part of agroforestry management practices to control water use. Pruning narrows the xylem vessels in *Senna spectabilis* and reduces the rate of transpiration and water consumption (Namirembe et al., 2009). It reduces the dipping diameter of jujube plant, which in turn increases the soil water storage (Chen et al., 2016). Wei et al. (2014) found a decline in the rate of sap flow in pruned jujube plants, compared with non-pruned plants, especially during the flowering and fruit enlargement periods. Moreover, wedge shapes are observed to form in dead tissues at the cut surfaces of pruned grapes, which affect the properties of catheter and sieve tubes and cause a significant decline in the sap flow rate (Zhao, 2013). Many studies showed that pruning is an effective method for ensuring the normal growth of jujube under drought or water deficit conditions (Chen et al., 2016; Wang et al., 2017; Zhang et al., 2017).

Studies of pruning were mainly focused on a short timescale, and there was little research on the effect of pruning on interannual variation of soil water conditions, especially in fragile ecological environments. Moreover, there were few well-structured scientific experiments or quantitative analyses concerning pruning intensity and its effect on crop yield and water use efficiency (WUE). In this study, the effects of pruning intensity on the spatiotemporal variation of soil moisture and on the tree growth characteristics of jujube plants were determined under natural rainfall conditions in the hilly Loess Plateau Region. The aims of the study were to evaluate the effects of pruning intensity on soil moisture, yield and WUE of jujube plantations, and to find a suitable pruning intensity for soil water conservation, recovery of dried soil layer and soil sustainable productivity. It is our hope that this study could provide scientific reference to

prevent environmental degradation in the hilly Loess Plateau Region and to promote the sustainable cultivation of jujube economic forests in hilly regions.

2 Materials and methods

2.1 Study area

The field experiment was conducted at Mizhi Experimental Station, Northwest A&F University, Shaanxi Province, Northwest China (37°25'N, 108°49'E; 892 m a.s.l.). The study area locates in the hinterland of the Loess Plateau with hills and gullies on a slope of 8°–12° and with severe soil erosion. It is characterized by a typical semi-arid temperate climate with annual mean temperature of 8.5°C, latent evaporation of 1650.0 mm, total radiation of 582.7 kJ/cm^2, total sunshine duration of 2761 h and mean annual rainfall of 451.6 mm, which mainly falls from July to September. We classified the years 2012, 2013 and 2014 as "wet years" with annual rainfall of 608.3 mm, 529.8 mm and 526.0 mm, respectively, and the year 2015 as "dry year" with annual rainfall of 359.4 mm based on the fifty years of meteorological data and the classification standards of hydrological years (Zhang et al., 2008).

The soil is uniform in texture in the 0–300 cm soil layer, with silt, sand and clay fractions of 7.7%, 47.8% and 44.5%, respectively. Mean bulk density of the soil is 1.31 g/cm^3 in the upper 300 cm soil layer. The soil field capacity by mass is 22.0%, with a wilting point of 5.5%. The water table is >50 m below ground.

2.2 Experimental design

Four similar horizontal terraces were selected on the southern slope (about 5°), where dwarf and densely jujube trees were cultivated in 2000 and regularly pruned in each year. Each horizontal terrace was treated as a separate plot and each plot was approximately 1.0 hm^2. The plant spacing was 3 m×2 m, with a density of 1666 plants/hm^2 in jujube plantations. We set four treatments for the jujube plant. They were control (CK), light (C_1), medium (C_2) and high (C_3) pruning intensities during the jujube growing periods of 2012–2015 (Fig. 1; Table 1). CK was the regular and the lowest pruning intensity. Plants were pruned as the standards described in Table 1. Pruning checks were conducted every seven days. Approximately six jujube plants were randomly selected as replicates for each treatment.

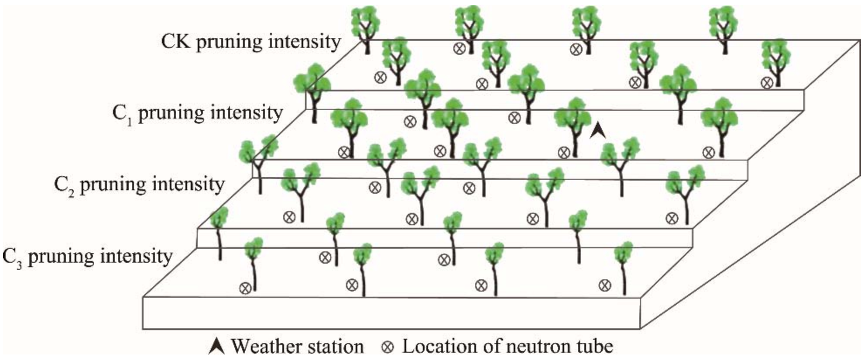

Fig. 1 Layouts of the experimental plots and the jujube plants under four pruning intensities at Mizhi Experimental Station in the hilly Loess Plateau Region. CK, control; C_1, light; C_2, medium; C_3, high.

Table 1 Standards of jujube plants under four pruning intensities

Pruning intensity	Plant height after pruning (cm)	Number of leading shoots remaining	Total length of lateral branch remaining (cm)
CK	220	4	575–625
C_1	200	3	425–475
C_2	180	2	275–325
C_3	160	1	125–175

Note: CK, control; C_1, light; C_2, medium; C_3, high.

Only robust branches were selected as leading shoots. Thin and diseased branches were also pruned, but no branch was left below leading shoots. Dislocation was used to prune leading shoots and lateral branches to avoid the mutual occlusion among the branches and ensure sufficient access to sunlight. Pruned leading shoots were hardly changed in the following year, so pruning was mainly used to control the length of lateral branches.

Around each experimental plant, a 100 cm deep ditch was excavated and then covered with thick plastic around the inner ditch walls to avoid soil moisture from the surrounding area influencing the experimental plot. Loess soil in this area was loose and had good infiltration capacity, so it was well-drained and had no runoff or deep percolation under low rainfall intensity conditions (light rainy days with rainfall of <10 mm/d account for 90%–97% of the total number of rainy days). Therefore, the natural environmental condition of the four terraces were similar. No fertilizer or irrigation was applied during the experimental period.

2.3 Data acquisition

2.3.1 Soil moisture

A neutron moisture gauge (CNC503B, Super Energy Nuclear Technology Limited, Beijing, China) was used to monitor soil water content to a depth of 300 cm for each treatment. A neutron tube was mounted 50 cm to the west side of the jujube plant roots and monitoring was conducted every 15 d at soil depth intervals of 20 cm. We corrected the neutron probes every three months and then calculate the soil water content based on a correction equation. Considering the inaccuracy of neutron method in measuring surface soil water content, we used oven-drying method to determine the soil water content in the 0–20 cm soil layer.

2.3.2 Meteorological parameters

A small meteorological instrument (BJJW-4, Beijing Yungen Technology Company Limited, Beijing, China) was installed at the experimental station. The meteorological parameters monitored were sunshine duration (SH; h), air temperature (T; °C), rainfall (P; mm), soil heat flux (G; W/m^2), relative humidity (RH; %), solar radiation (R; W/m^2), wind speed (u; m/s) and solar net radiation (R_n; W/m^2). Meteorological data were recorded every 30 min.

2.3.3 Growth indicators of Jujube

The growth indicators included: leading shoots (number), lateral branches (number, length and diameter), shed shoots (number, length and diameter; ten shed shoots were selected from east, west, north and south directions, respectively), fruits and leaves (number, transverse and longitudinal diameter; ten fruits or leaves were selected from east, west, north and south directions, respectively), weight of single fresh fruit at the fruit ripenning stage (30 fruits were randomly selected and their average weight was calculated) and yield (total weight; all fruits of the plants in each treatment). Lengths were measured using a tape (cm) and diameters were measured using a vernier caliper (mm). These measurements were taken every seven days from May to October in each year.

2.4 Statistical analyses

2.4.1 Soil water storage

$$\mathrm{SWS}_{0-300\ \mathrm{cm}} = \sum_{i=1}^{n}\left(\theta_i \times h_i\right), \tag{1}$$

where $\mathrm{SWS}_{0-300\ \mathrm{cm}}$ is the soil water storage in the 0–300 cm soil layer (mm); θ_i is the soil volumetric water content in the i^{th} soil layer (cm^3/cm^3); and h_i is the soil thickness in the i^{th} soil layer (mm; h_i=200 mm in any soil layer in this study).

2.4.2 Coefficient of variation (CV)

$$\mathrm{CV} = \frac{S}{\overline{X}} \times 100\%, \tag{2}$$

where CV is the coefficient of variation (%); S is the standard deviation; and $\overline{X}$ is the average

value. CV reflects the degree of discretization of the random variables. CV≥100% indicates strong variability of the random variables, 10%≤CV<100% indicates medium variability of the random variables and CV<10% indicates weak variability of the random variables (Zhang et al., 2016).

2.4.3 Water balance equations

The water balance equations for forests are as follows:

$$\Delta S=\left(P+I\right)-\left(C+ET+O+D\right), \tag{3}$$

$$\Delta S=S_{\text{initial}}-S_{\text{present}}, \tag{4}$$

where ΔS is the change in soil water storage in the 0–300 cm soil layer (mm); P is the rainfall (mm); I is the irrigation amount (mm); C, ET, O and D are the canopy interception, evapotranspiration, surface runoff and deep percolation (mm), respectively, and they are the depletive variables of soil moisture; S_{initial} is the initial soil water storage (mm); and S_{present} is the present soil water storage (mm).

In this study, canopy interception was not considered because pruned jujube trees had small crowns and rainfall intensity was limited in the study area. Deep percolation was ignored because ground water table was >50 m and the tested plot was horizontal and had an angle of inclination toward the mountain interior. Surface runoff was excluded because the soil in the study area had strong hydraulic conductivity. No irrigation was applied during the study period. Therefore, Equation could be rewritten as:

$$ET=P-\Delta S. \tag{5}$$

2.4.4 Index of soil desiccation

We used the degree of soil water deficit to obtain a more accurate and quantitative description of the intensity of soil desiccation according to the following formula (Yi et al., 2009):

$$K=\left(\theta_a-\theta\right)/\theta_a\times 100\%, \tag{6}$$

where K is the soil desiccation index, which represents the degree of soil water deficit (dimensionless); θ_a is the stable field capacity (cm^3/cm^3), accounting for 60% of the field capacity (13.2% in this study); and θ is the soil volumetric water content (cm^3/cm^3). According to the study of Li (1983), the stable field capacity represents the original soil moisture regime below the typical layer (200 cm) of infiltration from surface water, without the influence of soil evaporation and root water uptake. We divided the intensity of soil desiccation into four grades based on the K values: serious water deficit, when K value is >50%; moderate water deficit, when K value is 25%–50%; minor water deficit, when K value is 0–25%; and no deficit, when K value is <0.

2.4.5 Biomass of jujube

The biomass of each growth part of jujube is calculated as follows (She et al., 2015):

$$B_{\text{b}}=0.002D_{\text{b}}^{1.564}L_{\text{b}}^{1.016}, \tag{7}$$

$$B_{\text{s}}=0.005D_{\text{s}}^{1.02}L_{\text{s}}^{1.078}, \tag{8}$$

$$B_{\text{l}}=T_{\text{l}}^{0.901}V_{\text{l}}^{1.374}\times 4.568\times 10^{-5}, \tag{9}$$

$$B_{\text{f}}=0.631T_{\text{f}}^{3.6011\times 10^{-8}}V_{\text{f}}^{0.999}, \tag{10}$$

where B_{b}, B_{s}, B_{l} and B_{f} are the biomasses (fresh weight) of new branches, shed shoots, leaves and fruits (g), respectively; D_{b} and D_{s} are the diameters of new branches and shed shoots (mm), respectively; L_{b} and L_{s} are the lengths of new branches and shed shoots (mm), respectively; T_{l} and T_{f} are the transverse diameters of new leaves and fruits (mm), respectively; and V_{l} and V_{f} are the longitudinal diameters of new leaves and fruits (mm), respectively.

2.4.6 Water use efficiency (WUE)

WUE of different treatments was calculated using the following equation (Hussain and Al-Jaloud,

1998):

$$\mathrm{WUE} = Y/ET\,, \tag{11}$$

where WUE is the water use efficiency (kg/m^3); Y is the fresh fruit yield (kg/hm^2); and ET is the evapotranspiration, as defined in Equation 5.

2.4.7 Statistical methods

All statistical analysis was performed using Microsoft Excel 2010 (Microsoft Inc., Redmond, Washington, USA) and SPSS 16.0 (SPSS Inc., Chicago, IL, USA). The significant difference analysis was performed by one-way ANOVA.

3 Results

3.1 Temporal variation of soil water storage

Total rainfall during the jujube growing period (from May to October) was 419.2 mm in 2012, 492.2 mm in 2013, 413.8 mm in 2014 and 250.4 mm in 2015 (Fig. 2), accounting for 69%, 94%, 79% and 70% of the annual rainfall, respectively. These results suggested a great variation of rainfall during the four years.

Correspondingly, significant fluctuations in soil water storage were observed during the jujube growing period of 2012–2015 (Fig. 2). In May 2012, initial soil water storage was in the order of C_2>CK>C_1>C_3 pruning intensity, but this order was C_3>C_2>C_1>CK after July 2012 due to soil moisture infiltration, transport and redistribution. Compared with CK pruning intensity, soil water storage in 2012–2015 improved by 6.1–18.3, 14.4–40.0 and 24.3–63.3 mm under C_1, C_2 and C_3 pruning intensities, respectively.

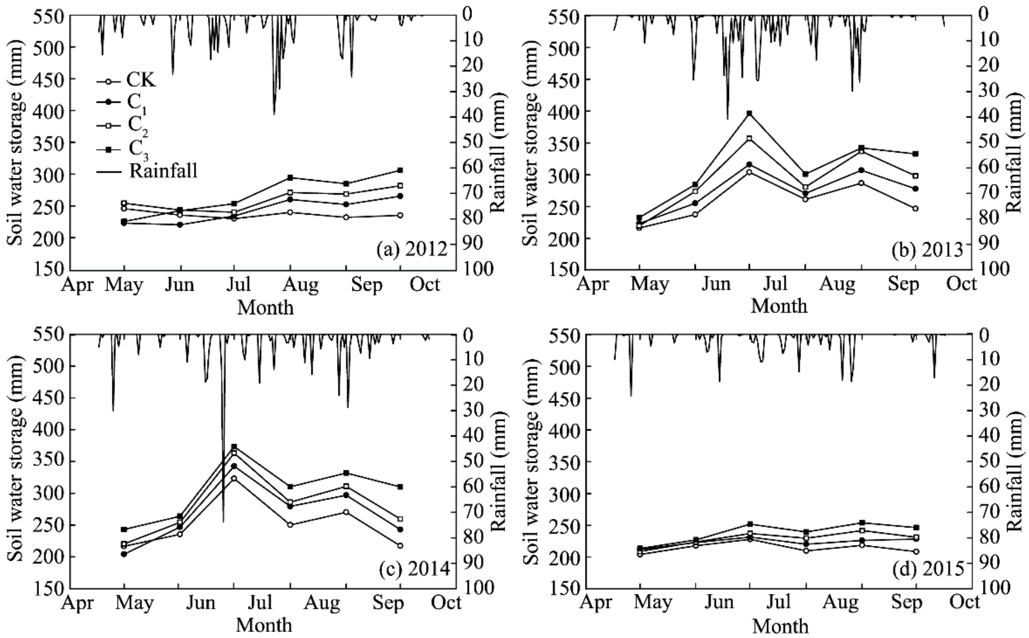

Fig. 2 Variation dynamics of average monthly soil water storage and rainfall in the 0–300 cm soil layer under four pruning intensities (CK, control; C_1, light; C_2, medium; C_3, high) of jujube plantations in (a) 2012, (b) 2013, (c) 2014 and (d) 2015

Table 2 lists the average soil water storage during the jujube growing period of 2012–2015 under four pruning intensities. The average soil water storage was highest in 2013 (a high rainfall year) and lowest in 2015 (a low rainfall year) under all pruning intensities. Although there was a similar amount of rainfall in 2012 and 2014, the differences in the average soil water storage among the four pruning intensities were larger in 2014 than in 2012. This result may be attributed to the influence of more rainfall in 2013.

Table 2 Average soil water storage of jujube plantations under four pruning intensities during the jujube growing period of 2012–2015

Pruning intensity	Soil water storage (mm)			
	2012	2013	2014	2015
CK	236.4^{c}	271.6^{c}	252.2^{c}	214.1^{bc}
C_1	242.6^{bc}	289.8^{bc}	268.7^{b}	223.2^{b}
C_2	260.4^{b}	311.6^{b}	284.0^{b}	228.4^{ab}
C_3	267.8^{a}	334.8^{a}	305.4^{a}	238.3^{a}

Note: Different lowercase letters within the same column represent significant differences of soil water storage under four pruning intensities for the same year at $P<0.05$ level.

3.2 Vertical distributions of soil moisture

The depths of soil moisture infiltration during the growing period of 2012–2015 under four pruning intensities of jujube plantations are shown in Figure 3. Soil moisture varied greatly in the upper soil layer and slowly in the deep soil layer. The CV under four pruning intensities changed from medium variability to low variability from the upper to the deep soil layer (Fig. 3e). Compared with the soil moisture in 2012, it infiltrated to the depths of 240, 220, 200 and 180 cm in 2013 under C_3, C_2, C_1 and CK pruning intensities, respectively. Because rainfall in 2014 was lower than that in 2013, soil moisture was reduced in the upper soil layer, but the depths of soil moisture infiltration increased to 280, 260, 240 and 200 cm under C_3, C_2, C_1 and CK pruning intensities, respectively. This might be attributable to the hysteresis effect of soil moisture movement. In addition, in the dry year (2015), the depths of soil moisture infiltration increased under C_3 and C_2 pruning intensities (>300 and 260 cm, respectively) but decreased under C_1 and CK pruning intensities (220 and 160 cm, respectively). This suggests that greater pruning intensity is better for the dried soil layer recovery of the deep soil layer.

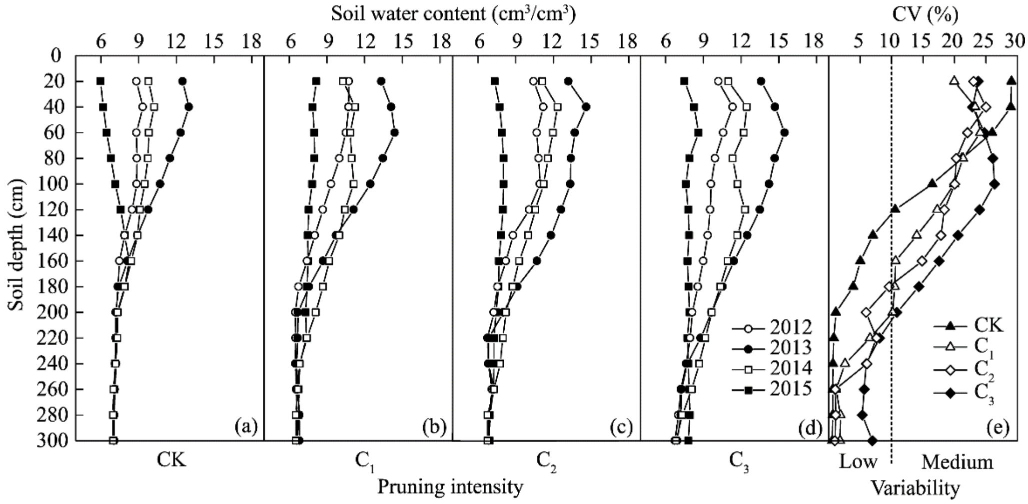

Fig. 3 Vertical distributions of soil water content in the 0–300 cm soil layer under (a) CK, (b) C_1, (c) C_2 and (d) C_3 pruning intensities and (e) coefficient of variation (CV) of soil water content during the jujube growing period of 2012–2015

3.3 Soil water deficit

Tables 3–6 list the degrees and statuses of soil water deficit under four pruning intensities during the jujube growing period of 2012–2015. Under CK pruning intensity, there was a moderate soil water deficit in the entire 0–300 cm soil layer in 2012, which then alleviated in the upper soil layer in 2013 due to heavy rainfall. Therefore, the decreased rainfall aggravated the soil water deficit. There was a moderate soil water deficit in the 0–300 cm soil layer (except that in the 20–40 cm soil layer) in 2014 and a serious soil water deficit in 2015 in the 0–60 cm soil layer. For

other pruning intensities, different degrees of soil water deficit were observed over the four experimental years. In 2012, soil water deficit statuses under C_1, C_2 and C_3 pruning intensities were minor in the 0–80, 0–120 and 0–80 cm soil layers, respectively. In 2013, there was no soil water deficit in the 0–60 cm soil layer under C_1 pruning intensity, 20–100 cm layer under C_2 pruning intensity and 0–120 cm layer under C_3 pruning intensity. However, in 2014, soil water deficit statuses were minor in the 0–140 cm soil layer under both C_1 and C_2 pruning intensities, and in the 0–180 cm soil layer under C_3 pruning intensity. In 2015, soil water deficit was moderate across all the soil layer under all pruning intensities.

Table 3 Status of soil water deficit under CK pruning intensity during the jujube growing period of 2012–2015

Soil layer (cm)	2012		2013		2014		2015	
	Deficit degree (%)	Deficit grade	Deficit degree (%)	Deficit grade	Deficit degree (%)	Deficit grade	Deficit degree (%)	Deficit grade
0–20	33.1	Moderate	5.3	Minor	25.8	Moderate	54.8	Serious
20–40	29.2	Moderate	1.5	Minor	22.5	Minor	53.1	Serious
40–60	33.1	Moderate	6.4	Minor	25.6	Moderate	51.0	Serious
60–80	32.8	Moderate	12.9	Minor	26.3	Moderate	48.5	Moderate
80–100	33.0	Moderate	18.8	Minor	28.1	Moderate	45.9	Moderate
100–120	35.7	Moderate	26.1	Moderate	31.0	Moderate	42.5	Moderate
120–140	40.3	Moderate	32.6	Moderate	32.4	Moderate	40.2	Moderate
140–160	43.3	Moderate	38.6	Moderate	36.3	Moderate	37.7	Moderate
160–180	44.3	Moderate	43.8	Moderate	40.2	Moderate	40.1	Moderate
180–200	45.4	Moderate	45.6	Moderate	44.5	Moderate	44.3	Moderate
200–220	45.5	Moderate	45.5	Moderate	44.6	Moderate	45.5	Moderate
220–240	45.3	Moderate	46.0	Moderate	45.7	Moderate	46.1	Moderate
240–260	46.2	Moderate	46.5	Moderate	47.0	Moderate	46.3	Moderate
260–280	46.5	Moderate	46.4	Moderate	47.2	Moderate	46.7	Moderate
280–300	46.5	Moderate	46.9	Moderate	47.2	Moderate	46.7	Moderate

Table 4 Status of soil water deficit under C_1 pruning intensity during the jujube growing period of 2012–2015

Soil layer (cm)	2012		2013		2014		2015	
	Deficit degree (%)	Deficit grade	Deficit degree (%)	Deficit grade	Deficit degree (%)	Deficit grade	Deficit degree (%)	Deficit grade
0–20	18.6	Minor	–1.0	None	22.1	Minor	38.2	Moderate
20–40	18.7	Minor	–7.0	None	14.8	Minor	40.4	Moderate
40–60	20.4	Minor	–9.1	None	17.7	Minor	39.5	Moderate
60–80	24.2	Minor	2.0	Minor	17.0	Minor	39.3	Moderate
80–100	29.3	Moderate	5.6	Minor	15.6	Minor	40.7	Moderate
100–120	34.2	Moderate	15.6	Minor	21.0	Minor	42.8	Moderate
120–140	39.0	Moderate	26.3	Moderate	24.3	Minor	43.3	Moderate
140–160	43.7	Moderate	34.1	Moderate	30.5	Moderate	43.2	Moderate
160–180	48.9	Moderate	42.5	Moderate	34.2	Moderate	43.8	Moderate
180–200	49.2	Moderate	49.2	Moderate	38.5	Moderate	44.6	Moderate
200–220	49.2	Moderate	49.3	Moderate	43.9	Moderate	44.2	Moderate
220–240	49.2	Moderate	48.5	Moderate	48.2	Moderate	48.1	Moderate
240–260	48.7	Moderate	49.5	Moderate	49.4	Moderate	48.8	Moderate
260–280	49.7	Moderate	48.3	Moderate	49.0	Moderate	49.0	Moderate
280–300	49.7	Moderate	48.3	Moderate	49.0	Moderate	49.5	Moderate

Table 5 Status of soil water deficit under C_2 pruning intensity during the jujube growing period of 2012–2015

Soil layer (cm)	2012		2013		2014		2015	
	Deficit degree (%)	Deficit grade	Deficit degree (%)	Deficit grade	Deficit degree (%)	Deficit grade	Deficit degree (%)	Deficit grade
0–20	20.9	Minor	0.1	Minor	15.8	Minor	44.4	Moderate
20–40	15.2	Minor	–10.7	None	6.5	Minor	41.4	Moderate
40–60	19.1	Minor	–3.9	None	9.3	Minor	40.0	Moderate
60–80	17.9	Minor	–1.5	None	12.3	Minor	39.1	Moderate
80–100	17.2	Minor	–1.1	None	14.9	Minor	39.1	Moderate
100–120	23.6	Minor	4.4	Minor	20.0	Minor	39.4	Moderate
120–140	33.3	Moderate	10.5	Minor	24.3	Minor	40.7	Moderate
140–160	37.6	Moderate	18.9	Minor	29.6	Moderate	41.9	Moderate
160–180	42.7	Moderate	30.8	Moderate	33.6	Moderate	42.2	Moderate
180–200	44.9	Moderate	39.2	Moderate	37.6	Moderate	43.6	Moderate
200–220	48.7	Moderate	48.0	Moderate	39.5	Moderate	44.8	Moderate
220–240	48.2	Moderate	48.1	Moderate	41.2	Moderate	44.8	Moderate
240–260	46.1	Moderate	45.0	Moderate	44.8	Moderate	45.2	Moderate
260–280	47.7	Moderate	47.8	Moderate	48.7	Moderate	47.3	Moderate
280–300	47.7	Moderate	47.8	Moderate	48.7	Moderate	47.7	Moderate

Table 6 Status of soil water deficit under C_3 pruning intensity during the jujube growing period of 2012–2015

Soil layer (cm)	2012		2013		2014		2015	
	Deficit degree (%)	Deficit grade	Deficit degree (%)	Deficit grade	Deficit degree (%)	Deficit grade	Deficit degree (%)	Deficit grade
0–20	22.7	Minor	–3.1	None	16.8	Minor	43.2	Moderate
20–40	14.1	Minor	–11.3	None	5.7	Minor	37.4	Moderate
40–60	19.9	Minor	–17.2	None	7.4	Minor	34.8	Moderate
60–80	24.8	Minor	–11.3	None	14.1	Minor	40.3	Moderate
80–100	27.1	Moderate	–7.8	None	11.3	Minor	42.5	Moderate
100–120	27.6	Moderate	–2.3	None	6.7	Minor	40.9	Moderate
120–140	29.1	Moderate	5.3	Minor	11.4	Minor	40.4	Moderate
140–160	31.8	Moderate	13.3	Minor	17.2	Minor	41.4	Moderate
160–180	35.1	Moderate	20.2	Minor	21.6	Minor	40.8	Moderate
180–200	38.5	Moderate	26.9	Moderate	26.8	Moderate	40.1	Moderate
200–220	39.7	Moderate	33.4	Moderate	30.6	Moderate	41.5	Moderate
220–240	42.1	Moderate	41.5	Moderate	34.4	Moderate	40.9	Moderate
240–260	45.3	Moderate	44.9	Moderate	38.8	Moderate	40.3	Moderate
260–280	46.9	Moderate	45.5	Moderate	44.5	Moderate	40.0	Moderate
280–300	48.9	Moderate	47.6	Moderate	48.3	Moderate	40.9	Moderate

3.4 Soil water balance

Changes in soil water storage under four pruning intensities in each soil layer were calculated in 2013, 2014 and 2015 (Fig. 4). Positive value indicated a soil moisture surplus, while negative value denoted a deficit. There were large differences in the vertical distribution of changes in soil water storage in the three years. In 2013, soil moisture recharged in the 0–300 cm soil layer under four pruning intensities (Fig. 4a). In 2014, soil water deficit was observed in the upper layer under CK, C_1 and C_2 pruning intensities (Fig. 4b). However, in 2015, changes in soil water storage under all pruning intensities were negative (Fig. 4c). Figure 4 also shows that in any

hydrological year, greater pruning intensity would result in greater soil moisture supply and less soil water deficit. From 2013 to 2015, changes in soil water storage in the 0–300 cm soil layer under CK, C_1, C_2 and C_3 pruning intensities were –40.6, –20.5, 6.4 and 26.8 mm, respectively.

3.5 Effects of pruning intensity on fresh biomass of jujube

Figure 5 shows the fresh biomass of each jujube organ at the fruit ripening stage under four

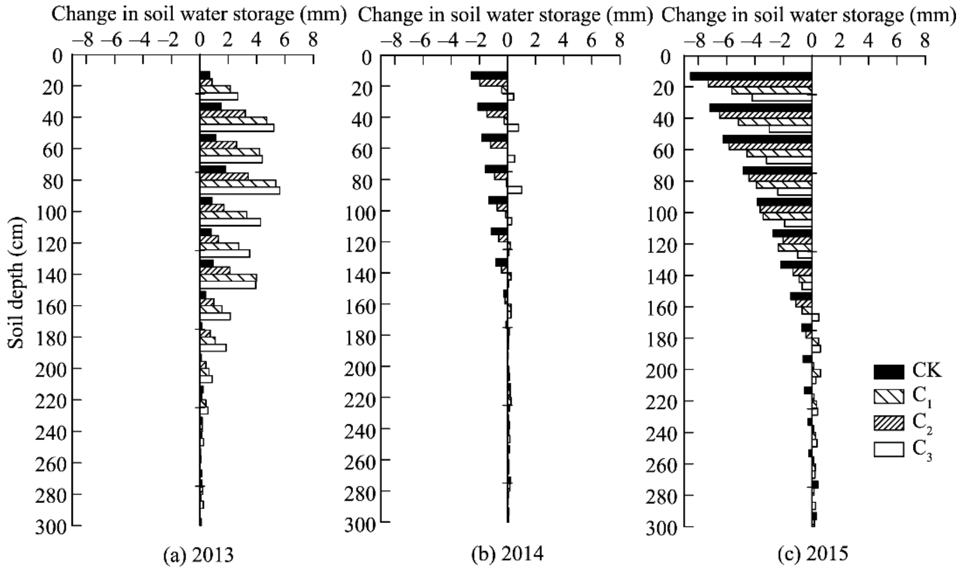

Fig. 4 Changes in soil water storage under CK, C_1, C_2 and C_3 pruning intensities in (a) 2013 (wet year), (b) 2014 (wet year) and (c) 2015 (dry year)

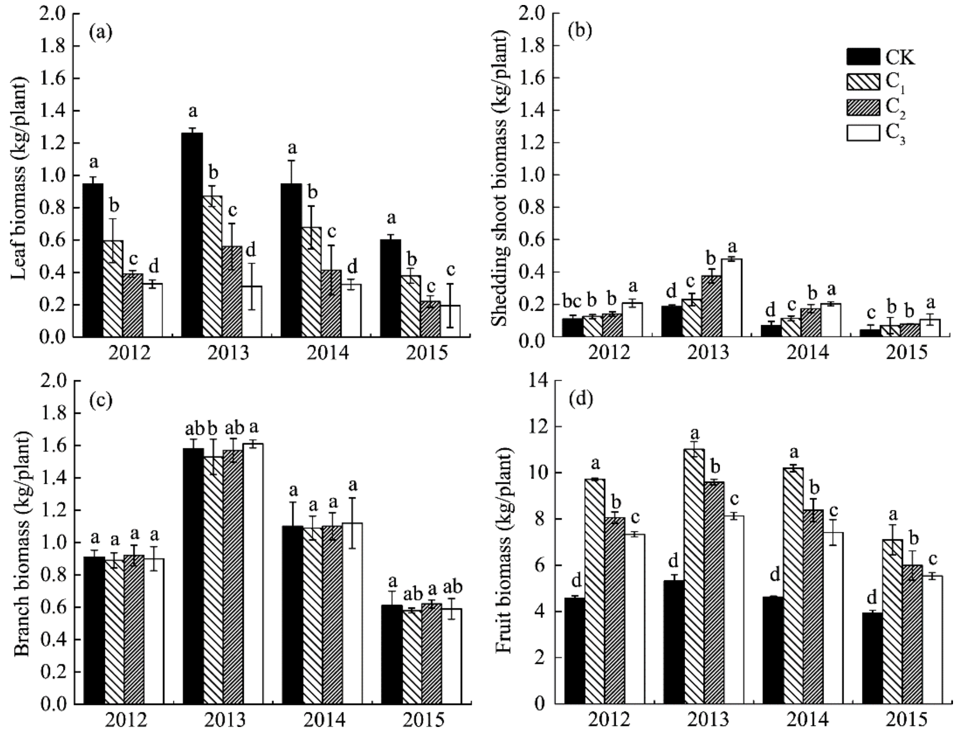

Fig. 5 Fresh biomass in (a) leaves, (b) shed shoots, (c) branches and (d) fruits of jujube plants under CK, C_1, C_2 and C_3 pruning intensities at the fruit ripening stage during the growing period of 2012–2015. Different lowercase letters within the same year represent significant differences among four pruning intensities at $P<0.05$ level according to LSD multiple tests. Bar means the standard deviation.

pruning intensities. Jujube plants had the highest leaf biomass under CK pruning intensity, which was significantly higher than those under C_1, C_2 and C_3 pruning intensities (P<0.05; Fig. 5a). Leaf biomass was negatively related to pruning intensity. However, shed shoot biomass increased with increasing pruning intensity (Fig. 5b). There were significant differences in shed shoot biomass between C_3 and all other pruning intensities (P<0.05) in all years. The highest fruit biomass was found under C_1 pruning intensity and the lowest under CK pruning intensity (Fig. 5d). Furthermore, no significant differences in branch biomass (including the pruned branches) were observed among any of the pruning intensities (P<0.05; Fig. 5c). Moreover, the biomass of each organ was highest in the wet year (2013) and lowest in the dry year (2015), indicating that rainfall is a decisive factor in jujube growth.

3.6 Effects of pruning intensity on water use efficiency (WUE)

Water consumption, fruit yield and WUE under four pruning intensities during the jujube growing period of 2012–2015 are shown in Figure 6. Soil water consumption was highest under CK pruning intensity and it was reduced with increasing pruning intensity, which suggested that greater pruning intensity resulted in better soil water conservation. Pruning significantly improved fresh fruit yield and WUE of jujube plants. Fresh fruit yields were highest under C_1 pruning intensity with the values of 6897.1–13,059.3 kg/hm^2, which were 2758.4–4712.8, 385.7–1432.1 and 802.8–2331.5 kg/hm^2 higher than those under CK, C_2 and C_3 pruning intensities in 2012–2015, respectively. However, C_3 pruning intensity had the highest WUE values (2.92–3.13 kg/m^3), which were 1.6–2.0, 1.1–1.2 and 1.0–1.1 times greater than those under CK, C_1 and C_2 pruning intensities, respectively. Fruit yield varied among different years. Although fruit yield in 2015 was approximately half of that in 2013, WUE was highest in this year, which highlighted the potential contribution of pruning to water-limited areas.

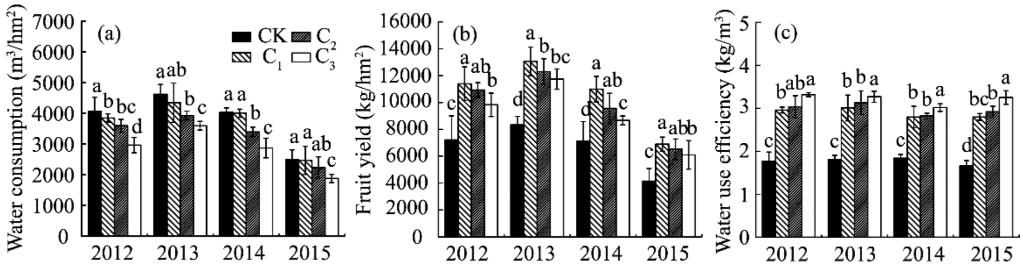

Fig. 6 Water consumption (a), fruit yield (b) and water use efficiency (c) under four pruning intensities during the jujube growing period of 2012–2015. Different lowercase letters within the same year represent significant differences among four pruning intensities at P<0.05 level according to LSD multiple tests. Bar means the standard deviation.

4 Discussion

Previous studies showed that 0–200 cm soil depth was the main layer of rainfall infiltration and plant root distribution in the hilly Loess Plateau Region (Liu et al., 2013; Wang et al., 2015). Thus, soil moisture in this depth has been usually considered in relevant studies. For jujube trees, Ma et al. (2012) showed that root intersects of one-year-old tree were concentrated in 0–40 cm soil layer, and four-year-old, eight-year-old and eleven-year-old tree root intersects were mainly in 0–60 cm soil layer. However, Liu et al. (2014) found that root growth extended to the deep soil layer (>200 cm) to absorb more water as jujube water requirements were not met by rainfall or drip irrigation. Wang et al. (2017) showed that the depth of soil moisture infiltration reached 460 cm after cutting jujube tree trunks for three consecutive years. In our study, the depth of soil moisture was >300 cm under C_3 pruning intensity. These results indicated that the commonly used soil depth is suitable for test needs. However, a greater depth (>500 cm) should be considered for future research on soil ecology. In addition, in our experimental design, only 100 cm depth was excavated to avoid lateral soil water input to the sample trees, which was insufficient and should be expanded in future studies.

Stand transpiration accounted for over half of the total water consumption (Chen et al., 2016), thus, management measures are necessary to suppress plant transpiration and prevent soil desiccation. Pruning can be an effective way to reduce tree water use by changing the canopy architecture and reducing canopy leaf area, leading to an improvement in the soil water replenishment rate (Shelden and Sinclair, 2000; López et al., 2008; Hipps et al., 2014; Afonso et al., 2017). However, pruning of tree canopies should be at an appropriate intensity, or it may be more effectively coupled to the atmosphere, as it increases rather than decreases transpiration (Jarvis and Mcnaughton, 1986; Wullschleger et al., 2000). Jackson et al. (2000) found that only severe pruning of tree canopies reduced the water requirements of trees. Hipps et al. (2014) also argued that canopy thinning (removal of 30% of the lateral branches) had no effect on limiting water demand, whereas canopy reduction (removal of the outer 30% of all major branches) conserved soil moisture for up to three years. A similar phenomenon was observed in our study, that is, soil water storage increased under three pruning intensities (C_1, C_2 and C_3) compared to CK pruning intensity, and high (C_3) pruning intensity had better water conservation effects.

Although previous studies indicated that pruning of branches was indeed beneficial to the recovery of dried soil layer, there was no clear indication of the exact depth or degree of its recovery (Wei et al., 2014; Chen et al., 2016; Nie et al., 2017). In the present study, minor or moderate soil water deficit was observed under four pruning intensities. In addition, soil desiccation was somewhat alleviated with increasing pruning intensity. However, the recovery of dried soil layer mainly occurred in the upper soil layer, even under the high pruning intensity. This might be attributable to the extreme drought condition. We also found that the depth of soil moisture infiltration was enhanced and reached up to >300 cm under C_3 pruning intensity, indicating that pruning promotes the replenishment of deep soil moisture and the recovery of dried soil layer.

Leaf biomass was significantly lower under C_1, C_2 and C_3 pruning intensities compared to CK pruning intensity, while shed shoot biomass and fruit biomass were higher, leading to a higher fruit yield. This finding indicates that pruning improves the proportions of vegetative and generative plant parts (Ambroszczyk et al., 2007). Many researchers have found that pruning can improve fruit yield and quality by enabling greater access to light, water and nutrients (Reynolds, 1989; Seifi et al., 2011; Bhagawati et al., 2015). However, we also observed a non-linear relationship between pruning intensity and fruit yield. Jujube plants under C_1 pruning intensity had the highest yield, so pruning within a limited range of intensity had a positive effect. Jorquerafontena et al. (2014) found that yield and berries per plant decreased with increasing pruning intensity.

Pruning intensity increased the WUE partly because it markedly reduced the soil water consumption. Previous researchers proposed a conceptual "water-saving pruning measure" to control soil desiccation in jujube plantations (Zhao et al., 2012). According to this strategy, soil water content determines the fruit yield and fruit yield determines the tree size. Similarly, our results further implied that local average annual rainfall, soil moisture status and the physiological characteristics of jujube plants determine the yield and then the appropriate yield determines the canopy structure of tree. Zhao et al. (2012) showed that a sustainable water-saving pruning strategy is not only based on the maximum yield, but also should avoid excessive use of soil moisture for sustainable management of plantations. In the present study, compared with C_2 and C_3, although C_1 pruning intensity produced the highest yield, it had the lowest WUE. Furthermore, C_3 pruning intensity produced the highest WUE and also an acceptable yield. Therefore, in the range of pruning intensities tested, C_3 pruning intensity is recommended for its economic and ecological benefits. However, in order to obtain the optimal pruning intensity to improve yield and WUE, more pruning intensity gradients should be considered in future experiments.

5 Conclusions

Pruning is an effective way for conserving water resources in jujube plantations in the hilly Loess

Plateau Region. Soil water storage significantly increased during the jujube growing period of 2012–2015 under C_1, C_2 and C_3 pruning intensities, compared to CK pruning intensity. Pruning promoted soil moisture migration to the deep soil layer and improved the recovery of dried soil layer. Soil water change was positive both under C_2 and C_3 pruning intensities and negative under C_1 and CK pruning intensities in 2013–2015. Pruning promoted the reproductive growth (shed shoots biomass and fruit biomass) and inhibited the vegetative growth (leaf biomass), resulting in a high yield and WUE. The C_3 pruning intensity is recommended for its economic of jujube plants and ecological benefits.

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